

# News & Views

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## A Complex Adaptive Future

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Our great national philosopher, Yogi Berra, once said, “the future is not what it used to be.” Imagine what Sandia will be like in 2013 or 2018. More importantly, *imagine what we might want it to look like.* From today’s vantage point, we have the power to help shape that future—a future that is guaranteed to look very different from today. To help visualize tomorrow, it is sometimes instructive to look in the rear view mirror. Think back to 1993 and the major changes that had begun to cascade throughout the Lab as a result of the end of the Cold War. One need only to go back to September 11, 2001, and its aftermath to recognize that sudden and unexpected upheaval in our external environment can lead to large unpredictable consequences in both the short term and the long term. We are clearly living in a very dynamic time where constant change is a given, and adaptation is crucial for survival.


Although the future cannot be predicted, there are always environmental indicators, rarely strong, often weak, that can provide clues about what may happen. The challenge is to identify the meaningful indicators, and be prepared to adapt, prevent, or respond. Some trends are fairly obvious. The nation’s defense budget and the deficit, for example, have increased so suddenly and dramatically recently that these trends are unsustainable. Other trends are much more subtle, like the increasing emphasis in the scientific community on Complexity studies. Lots of “applied” Complexity Science is currently being done at the Lab, but our work has been largely unrecognized—much like bioscience several years ago. These efforts in Complexity tend to deal with dense, interconnected phenomena having non-linear causal connections (feedback) that are manifested in the real world as *complex adaptive systems* (CAS).

In historical terms, Complexity Science is still a very young field. It burst on the scene as a new force to be reckoned with when a group of staff scientists at Los Alamos’ Center for Non-

Linear Studies decided in the early 1980s to spin off a stand-alone entity devoted to the study of complex adaptive systems. The Santa Fe Institute is now a center for work in Complexity, but a Google search based on the terminology will reward you with over one million references.



Inside this issue



1...	A Complex Adaptive Future
3...	Complex Systems Studies and Applications: Why We Need a Strategy for Sandia
6...	Thoughts on Networked Sensors (SDACs)
7...	Can Complexity Science Help Us Understand What We Do Not Know?
9...	Cracking the Genetic Code: The Sequel
11...	Modeling and Simulation of Complex, Interdependent Adaptive Infrastructures
13...	The Earth System and Global Climate Change
14...	Modeling Human Adaptation to Climate Change as a Complex Systems Response



So, what is Complexity and how does it differ from other approaches to understanding systems? A system functions as a whole through the interaction of its constituent parts. *Systems thinking* considers the entire entity, its components

and the links between components. Since a system functions as an integrated whole, it can therefore have properties that are independent and distinct from those of its component parts. Such system properties have been termed *emergent* and are characteristic of CAS. Systems also have boundaries, and depending on how these are defined, the system can be described as either open or closed.

CAS occupy the important middle ground between two extremes: ordered systems characterized by lots of regularity, and chaotic systems dominated by randomness. Real systems that straddle and lie between stability and chaos are of great interest because they are so prevalent in the world around us. Some engineered systems like nuclear weapons are largely ordered and closed systems, and Sandia's overriding responsibility is to make such systems extremely reliable and predictable. We spend a lot of time and effort in order to anticipate and deal with the possible nasty excursions that can occur either from external environmental changes or subtle internal changes. The same goal of high reliability also applies to the design of robotic swarms,

sensors networks, and bug-free software. In the case of a nuclear weapon, even though we have a mostly closed predictable system, individual parts of subsystems over time will interact with each other as the weapon ages. Another familiar CAS example of unexpected maladies arising from aging is with people. The mechanistic or reductionist approach is initially adequate for the management of these kinds of systems because the tasks for maintenance are straightforward and repetitive, and the environment is largely stable. But as time progresses, emergent properties and unpredictable changes, especially those caused by feedback among subsystem components, could make knowing the viability of a nuclear weapon (and old people) problematic. Thus, for nuclear weapons and other systems of interest, we need to understand the potential role of emergence and uncertainty, which are characteristic features of CAS.

What does Complexity have to do with a 10-year vision for Sandia? Many of today's most challenging national security issues are not amenable to conventional engineering solutions. This trend will only increase in the future. Threats to national security are often manifested as dynamic, networked self-organizing systems composed of multiple kinds of human or non-human agents (e.g., terrorist groups, computer viruses/worms, etc.). Interactions at the local level

often lead to unexpected behavior or unintended consequences at the systems level, as the 9/11 attacks clearly demonstrated. Furthermore, these "systems of systems" are increasingly part of a new dynamic that includes humans as integral components.

We need to be developing new engineering methodologies so that Sandia's strengths as a systems engineering laboratory will be both broadened and deepened. There are whole classes of systems addressed by Complexity Science for which our traditional engineering core competencies are insufficient, namely, dynamically evolving systems that exhibit self-organizing behavior, adaptation, and randomness. To be at the leading edge of systems engineering in the future, we must not only develop a high degree of competency with the techniques and theory of Complexity, but we must also be at the leading edge of research and development that will facilitate practical applications and solutions. This might turn out to be Sandia's unique niche in this rapidly growing field.

A ten-year vision for the Laboratories should, in our opinion, include a prominent role for the study of CAS. To articulate a specific vision involving CAS would require identifying a series of goals of short-, intermediate- and long-term duration, and would entail identifying requisite staff needs, partners, investments and potentially

## ACG Weekly Brainstorm Sessions!!

Please join us for our weekly brainstorm sessions

every Friday, 9:00-11:00 a.m! Please check out the "upcoming events" on our web page for a list of scheduled topics. If you have a topic to suggest, please contact Simon Goldfine at [srgoldf@sandia.gov](mailto:srgoldf@sandia.gov) or 845-0917.





revolutionary applications, not to mention buy-in from senior management. From all this should flow a few BHAGs (Big Hairy Audacious Goals), each feeding off and reinforcing one another.

As part of the increasing recognition of Sandia's growing involvement with Complexity, we have put together this special issue of the *ACG News & Views*. The seven articles that follow represent a small sampling of the many robust activities ongoing at the Lab that could be classified under the umbrella of Complexity Science. In their overview article, Bob Floran and Gordon Osbourn provide a rationale as well as the beginnings of a strategy and roadmap; included is a visual snapshot of the numerous and diverse activities in Complexity throughout Sandia. Ray Harrigan argues for using Complexity to better understand self organization in robotic swarms; current initiatives

that envision the deployment of an SDAC multisensor distributed network must account for, and indeed take advantage of, emergent phenomena before such networks can successfully achieve their stated goal of exquisite precision awareness against global asymmetric threats. Nancy Hayden asks some penetrating questions about what we know or don't know about the systems all around us from a social science perspective, and how the various tools and concepts of Complexity Science might be able to provide valuable insights. Bob Glass and colleagues also ask questions, but these are directed at how interdependent adaptive infrastructures respond to disruptions; their disturbing conclusion is that business policies that encourage efficiencies make these infrastructures less robust. The complexity of information transmission in biological and engineered systems and the importance

of error control coding are described by Elebeoba May and others. And finally, two accompanying pieces by Diane Barton and Mark Boslough both deal with global climate change as a Complex System, but from very different perspectives. As an aid to better decision-making, Barton advocates using massively parallel simulation and modeling to better understand local/regional effects and their global societal implications. In contrast, Boslough describes the daunting technical challenge of modeling the complex dynamical interactions between the human population and a constantly evolving climate system over various time scales and at different levels of organization. As you read these articles and the literature in the field, we hope you will share our belief that this subject is going to dominate systems engineering in the future. ■

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## Complex Systems Studies and Applications: Why We Need a Strategy for Sandia

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**C**omplexity Science deals with systems with global properties that cannot be explained by understanding their component parts in isolation. Localized interactions often give rise to unexpected behaviors within

the overall system. Such complex systems exhibit both structured behavior and randomness at the same time.

There are several reasons why Sandia should strongly consider focusing on Complexity Science as a new technical thrust or line of business or even, if future events warrant, a new research foundation. First, Complexity Science provides a new way of thinking to

attack difficult, multifaceted system problems in both technical and non-technical areas that Sandia is increasingly called upon to address, the so-called "wicked problems" (see May and June *ACG News & Views*). These challenges cannot be solved using a traditional reductionist approach.

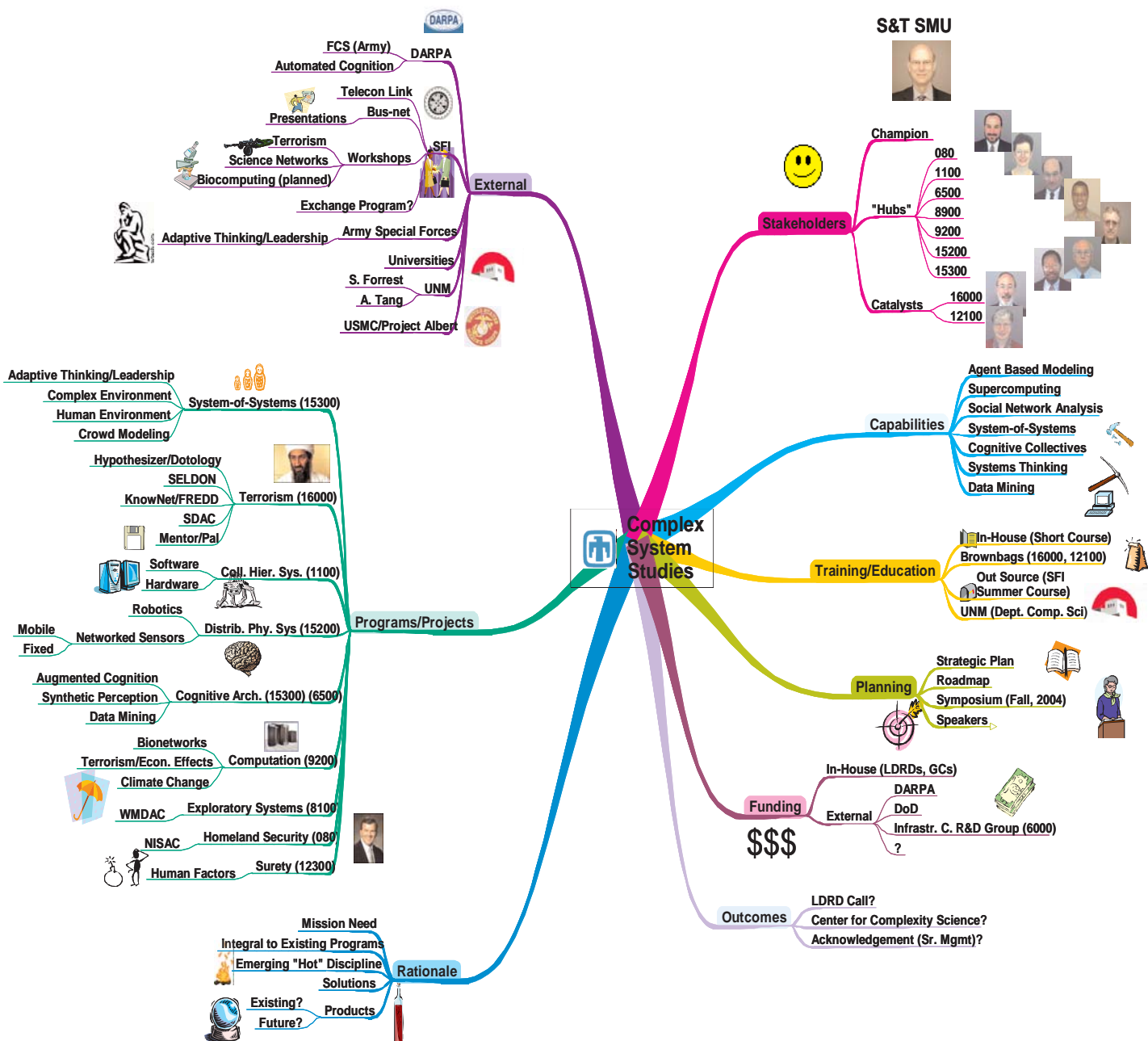
Second, Complexity Science already pervades numerous high profile R&D



projects that encompass a broad spectrum of interdisciplinary activities relevant to our national security missions—but often under the guise of being called something else. On-going efforts are numerous but scattered throughout the Lab and would benefit from a coherent strategic plan and roadmap.

Third, Sandia is well positioned to extend Complexity Science beyond a primarily theoretical exercise to an experimental activity leading to practical engineering utility. Sandia has essential resources to make major and unique contributions (e.g., large-scale computation and modeling capabilities) and is prepared

to take advantage of its close proximity to the Santa Fe Institute, the recognized world leader in this field. Exceptional technical impact is possible because of the Lab's interdisciplinary teaming, system-level thinking, and practical problem-solving emphasis. These traits are lacking in many of the small academic





modeling efforts that are common to this field.

And fourth, Sandia must be ready to respond to sudden transformations in the external environment (like 9/11), but also to subtle shifts. For example, to remain a leader in the scientific, technological and engineering enterprise, Sandia needs to continue its tentative embrace of the “softer” sciences; these disciplines are vital to solving complex, human-centric problems that increasingly intrude on our traditional mission space.

Complexity science and its applications can be a key enabler at the interfaces between bio-nano-info and cognition. Biological structures are of particular interest as complex adaptive systems that often serve as inspirations for engineered analogs. Agent-based software systems, large interconnected physical systems and self-assembling materials are examples of non-biological complex systems. In its broadest sense, these kinds of systems are ubiquitous and extend over many orders of magnitude scale, from interacting molecular networks that control cell behaviors to human societies and global economic systems.

A proposed complexity strategy for Sandia would have the following goals: (1) Bring a broader awareness of the utility of Complexity Science to Sandia missions and programs, (2) Conduct research in the theory and

methodology of complexity that includes a fundamental understanding of the organizing principles of hierarchical systems and how they evolve across multiple length scales (biological and non-biological), (3) Develop complexity-based engineering design tools to create new classes of smart microsystems, integrated nanosystems, and high-surety software systems consistent with our missions, (4) Strive to create breakthroughs in existing programs that require a more thorough understanding of complexity behavior than we currently possess, and (5) Develop external recognition for Sandia as a leader in complexity science-based engineering. Critical to achieving these goals are a mix of analytical tools that underpin most group efforts in Complexity Science at the Lab: agent-based modeling and simulation, network analysis, algorithm development, and data visualization. Trans-disciplinary teams will be needed to provide a bridge between the social sciences and traditional engineering.

A key objective will be to identify and capitalize on the underlying synergies linking several of the Lab’s most visible differentiating or emerging capabilities that deal with complexity applications, specifically, cognitive architectures; robotics and networked sensor arrays; and self-organizing/self-assembling computer

software and hardware.

Another important objective will be to extend and enrich our traditional capabilities so that we can be more effective in both our core missions as well as future missions; this will require paying increased attention to the social sciences—taking into account the most dynamic and influential part of the systems we deal with: the human element.

The accompanying figure known as a “mindmap,” is a current snapshot that illustrates the many and varied activities at the Lab in complex systems studies. Though hierarchical in concept, many of the individual nodes and branches have cross linkages which are not shown. Interestingly, the part of the diagram illustrating the numerous projects and programs that are ongoing can be thought of as a large massively parallel experiment. On the one hand, the many simultaneous pathways speed up the diffusion of complexity concepts throughout the Lab; on the other hand, they also allow us the luxury of hedging our bets that one of these efforts will eventually result in “the next big thing” for Sandia.

*Note: we would like to acknowledge the many Sandians who contributed to the thoughts expressed in this article. A much longer draft version including a proposed roadmap is available from Bob Floran. We encourage your feedback! ■*

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**“...to remain a leader in the scientific, technological and engineering enterprise, Sandia needs to continue its tentative embrace of the ‘softer’ sciences....”**

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## Thoughts on Networked Sensors (SDACs)

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**“Because of the non-deterministic complex nature of current ad hoc networks, these phenomena emerge in the system in ways that, as yet, are not well understood in terms of the behavior of the individual agents.”**

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The observations contained herein derive from nearly a decade of research into engineered collectives. Initially this research was stimulated by Sandia’s nuclear weapons program’s interest in advanced systems concepts. Unexpected behavior observed in networked machine systems was the motivating focus. This phenomenon is commonly referred to as “swarm behavior.” Catalyzed by NW’s initial seed investment, subsequent exploratory research supported by LDRD and DARPA investments has totaled over \$10M. This research provided foundational understanding of key characteristics of highly networked systems operating in the physical work. Going beyond the initial “swarm robot” research, this work now includes a broad spectrum of networked systems; so-called “engineered collectives.” Of particular importance to the SDAC (Sense, Decide, Act, Communicate) concept has been our research into networked sensor systems, most recently manifest in the TALON Grand Challenge.

**You cannot avoid the complexity associated with networked systems.**

New system level behaviors result when entities (frequently referred to as agents) are networked together and communicate information among themselves. Because of the non-deterministic complex nature of current ad hoc networks, these phenomena emerge in the system in ways that, as yet, are not well understood in terms of the behavior of the individual agents. It doesn’t matter whether the agents’ behaviors are static or adaptive, well engineered or ad hoc. Behaviors of the “system” born of the system-level associativity enabled by the network will arise.

**The numbers game is not always a winning equation.**

In most systems, the desired effect of increasing numbers is to increase overall performance. In some cases, synergistic effects can produce dramatic positive results. In other systems, increasing numbers can dramatically degrade performance and sometimes create dramatic and unacceptable side effects. Early work in parallel computing and the unpredicted effects of rolling brownouts in the power grid are examples of systems that suffered from growth in numbers. History and experience shows that it will be difficult to achieve dramatic improvement or avoid dramatic failure in large networked systems without focused systems-level engineering and analysis. We

are better at building complex systems than designing and engineering them.

**Physics matters.**

Much of the research into so called “emergent behaviors” to this point has focused on “disembodied behavioral agents.” Typically these are software entities programmed with specific behaviors to study, in a virtual domain, collective phenomena. There is no physical environment for the agents to interact with. Research on agents operating in the physical world (e.g., robots) however, demonstrates the additional critical influence of “localized” physical interactions on the overall behavior of networked systems. Localized physical interactions affect the local agent and can be propagated throughout the network frequently with highly non-linear, chaotic system level impacts. In real-world networked systems, localized physical interactions must be considered by systems engineers.

**Complexity issues affect design, deployment and understanding of sensor networks.**

The complexity effects that arise due to ad hoc networking and physical effects must be considered during sensor network design and deployment. Otherwise how can you know what type and how many sensors to deploy in what configuration? “More is better” is not necessarily true in these systems. The physical



characteristics of the communication network alone can give rise to strong non-linear effects that can degrade the overall performance of the network of sensors. For example, the reactive nature of the network makes communication attributes such as bandwidth, timing, etc. integral to the interpretation of communicated information. In addition, the whole purpose of an SDAC network is to provide information. But the same network effects that emerge during operation of the network also overlay the sensory data communicated by the network. You must be able to deconvolve network effects from sensor effects in order to be able to interpret the data provided by an extensive network of sensors.

**We can simulate collective behaviors of networked systems but we cannot predict performance—yet.**

Physics-based simulations of agents and their associated collective behaviors have been shown to behave similarly to physical agents operating in the real world. In fact, within restrictive environments (minimal coupling of environmental physics to agent behaviors) theorems of convergence have been successfully developed. But such is not the case for many realistic physical scenarios such as those envisioned as the application environments for SDACs. So while we can model performance we cannot claim to understand the performance of

networked systems. Approaches such as queuing mathematics have been used to model CSMA networks. However, significant work is needed to extend these techniques to provide analytical representations of the overall behavior of systems comprised of networked entities in which the individual physical agents (e.g., mobile sensor nodes) both adapt to their local environments and to the behavior of other elements within the system. We are in a period of exploration and discovery. Physical experimentation is severely limited by the cost and time to field highly networked sensor systems, as demonstrated both during the DARPA SensIT program and within Sandia's TALON program. Performance of iterative analysis through physical experimentation alone is thus virtually impossible. However, model-based simulation validated through well-engineered physical experimentation (not demos) can provide cost effective environments for iterative exploration and algorithm development.

### Conclusion

The use of small, cheap sensors collected into vast engineered arrays to provide exquisite situational awareness is a disruptive capability with incredible potential impact. But it will not happen if the system complexity issues that arise as a natural consequence of networking are not addressed. We will not know how many sensors to deploy in what

network configuration. Nor will we be able to interpret the information provided by such a network of sensors, static or adaptive. Sandia has a core group of research pioneers in the area of collective behaviors and they have the analysis tools to make progress. Past investments at Sandia have also provided a unique understanding of network effects in real-world agent-based systems. Coupling MEMS sensor development and remote system technologies with evolving modeling and simulation-based analysis tools (perhaps as part of the proposed  $\mu$ Talon initiative) can position Sandia to provide commanding complex systems engineering leadership to make the concept of exquisite situational awareness real. ■

## Can Complexity Science Help Us Understand What We Do Not Know?

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The fundamental principle of security and strategic warfare is to “know thy enemy.” Since September 11, the national security community has been struggling to do just that with respect to terrorist threats. Yet the nature of the terrorist

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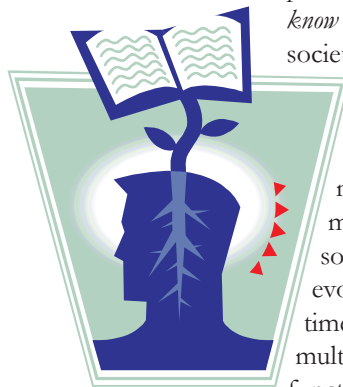


threat is that it is constantly changing. Furthermore, there is a dynamic, non-linear feedback between our responses to the threat—both militarily, in the media, and as a society—and its evolution.

These properties are the hallmarks of a complex system.

**What does complexity science offer to help us understand that which we do not know?**

The problem of knowing what we know about terrorism was articulated recently by Jerrold Post, one of the world's foremost terrorists experts, at a recent ACG-sponsored workshop that brought together terrorist experts, knowledge management experts, and computer scientists. In his words, our fundamental problem is that *"We do not know what we know."* Our society functions as a



complex, interconnected "system of systems" of diverse natures—biological, man-made, institutional, societal, natural—that evolve over a wide range of timeframes to perform multiple and different functions depending on the context. Understanding terrorism demands an analysis framework that is valid within each of these diverse systems, yet can also be applied across the interconnected whole. To complicate matters, our gaze must go beyond our own borders—to systems operative across different political, cultural, socioeconomic, religious and geographic boundaries.

Transcending the boundaries between these disciplines has, to date, been an insurmountable obstacle for researchers and analysts alike. This is due in no small part to the historical path of evolution of the social science disciplines, and the research methods adopted for their development. For the last half century, the social sciences have taken great pains to develop rigorous research methods that adhere to the scientific principles of investigation, yet, due to the nature of the systems they describe, these are not always satisfactory for investigating complex, cross-cultural issues. This is due not only to the diverse, evolutionary nature of the systems described within each, but also to the lack of common tools, vocabulary, and paradigms that are able to translate domain specific results across domains of expertise and into a larger problem context. The kinds of analysis frameworks that are needed include those that

- accommodate different system sizes and structures, different dynamical timeframes, and cooperative (or competitive) interactive processes between large and small components (e.g., for modeling emergency response teams and organizational structures under different failure modes)
- account for nonlinear cause and effect relationships of events that systems experience (e.g., for modeling cascading failures

initiated by trigger events and amplified by latent system failures)

- synergistically link components within and across networks (e.g., for modeling total economic and/or societal impacts)
- provide for positive and negative feedback depending on the character of the system, its environment, and the nature of the interactions between them (e.g., for modeling unintended consequences, or exploring the impact of foreign policy on multiple interest groups in the Middle East and their corresponding attitudes and relationships towards the U.S.).
- incorporate self-organizing, non-directed actions (e.g., for modeling terrorist adaptations to hardening our infrastructures)
- accurately reflect the dynamic, evolutionary nature of the systems of concern, and the co-dependent nature of that evolution.

The tools and methods of complexity science that have evolved in the last twenty years begin to provide such capabilities, at the same time that social science research methods are beginning to put more credence in theoretical investigations wherein the researcher is in a constant cyclical process of being guided in his/her queries by the data gathered in the field. Such methods have been termed "grounded theory." Using grounded theory as a process of social science



investigation closely mirrors the systems analysis process outlined by Garajedaghi for complex systems.

### So, is there hope for a meeting of minds and methods on the horizon?

Some of the tools and concepts for modeling engineering systems that have come out of complexity science are ideally suited for advancing research into social phenomenon. For example, the spread of group ideas and movements is captured in the concepts of diffusion, revolution, co-evolution, epochal evolution, and punctuated equilibrium. The concepts of learning and reasoning are captured by methods of cellular automata, genetic algorithms, evolutionary algorithms, and neural networks. Possible logical frameworks for rational decision-making can be modeled via decision trees, hierarchies, embedded networks. The topographical differences between networks and the dynamics that act upon them are now being understood as systems that can be random, scale-free, or evolve into giant stars. Furthermore, advances in computing power are leading us towards a unified capability to look at the concepts of the system dynamics we want to understand: the processes for change—adaptation, synchronization, innovation, learning; the initiators of change—strange attractors, clusters, hubs, tipping points, fault lines, bifurcation, phase transitions, levers; the agents of change—individual agents, meta-agents, swarms; and the characteristics of change—

robustness, stability, resilience, reliability, predictability, fragility, vulnerability, diversity.

*The beauty and power of complexity science, however, will lie in our utilization of these methods to continue to generate theory and test it against what we see in reality. In so doing, our hope is to be on a continual road of discovery: What do we know? What don't we know? How will we find out more about each? ■*

## Cracking the Genetic Code: The Sequel

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In his 1998 paper, *The Invention of the Genetic Code*, Brian Hayes details the decade long pursuit to break the genetic code hidden inside the DNA double helix discovered by James Watson and Francis Crick in 1953. Hayes recounts “how quickly a biochemical puzzle ... was reduced to an abstract problem in symbol manipulation.” This all-important quest for a golden fleece of sorts attracted quantitative scientists, accomplished in their respective fields, including the physicist, George Gamow, and coding theorist, Solomon W. Golomb. Experimental evidence from Marshall W. Nirenberg and J. Heinrich Matthaei of the National Institutes of Health eventually led to the cracking of the genetic code.

Unfortunately it also seemed to mark the end of fervent research into information and coding theoretical investigations of biological organisms.

From the early 1950s to the mid 1960s the focus of the code-cracking enthusiast was understandably on the protein-coding portion of DNA (the region that contains triplet nucleotide bases that represent amino acids which constitute proteins). Non protein-coding DNA sequences, pejoratively referred to as “junk DNA” have until recently been overlooked. Scientists are finding that these sequences are far from “junk” but rather some serve regulatory roles for genetic processes including the control of protein translation initiation. So it seems that the mystery of the double helix has not been completely unraveled. There is at least a second part to deciphering the information transmission protocols of biological systems, namely a need to crack the regulatory code of DNA.

### Why should an engineering laboratory like Sandia be interested in understanding the complex communication system of biological organisms?

Beside the potential impact on biological sensor development and the ability to model and ultimately develop defense mechanisms for bioagents that can be engineered to cause catastrophic damage, we can improve our current communication protocols by learning how biological

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“So it seems that the mystery of the double helix has not been completely unraveled.”

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organisms are able to communicate their genetic message efficiently in the presence of noise. Biologists may cringe at this idea, but let me suggest and echo the belief that at the heart of it all, the genetic system is fundamentally an engineering system. Or a parallel notion is

There are three general problems in communication, which we can loosely term packing, transmission, and security. Source codes (compression codes) help reduce the number of bits used to represent a message. Channel codes (error control codes) tackle the problem of efficiently transmitting the message over a noisy environment or channel. Cryptographic codes protect our message from eavesdroppers that can compromise our system. Years of theoretical research and funding have produced algorithms for addressing these challenges in engineering communication systems. If we can recognize the necessity of protecting inorganic information, it is not

the current genetic code is an error control code. Focusing on regulatory regions of DNA, we theorize that the transmission of genetic information can be viewed as a biological, cellular communication system that employs some method of error control (EC) coding to protect and recognize valid information regions and to correct for “transmission” errors (Figure 1: DNA replication is the genetic channel; transcription, protein translation initiation, protein translation elongation plus termination constitute the genetic decoder). The challenge is to determine the encoder given the received, noisy output of the genetic transmission channel. As one can imagine, communication engineers tend to be forward engineers and do not concern themselves with reverse engineering error control codes. In our quest to crack the genetic code, part two, our first challenge is to develop quantitative approaches to reverse engineer error control codes from noisy data. To this end, the initial phase of our research employed a three-prong approach to address the problem of detecting and reconstructing error control codes for engineered and biological systems. Approaches include: 1) Information theoretic studies of the genetic channel and EC encoded data streams, 2) Cryptographic exploration of RNA data streams, and 3) Investigation of the reverse engineering problem from an optimization framework. Our efforts have yielded insight

## Communication View of Genetics

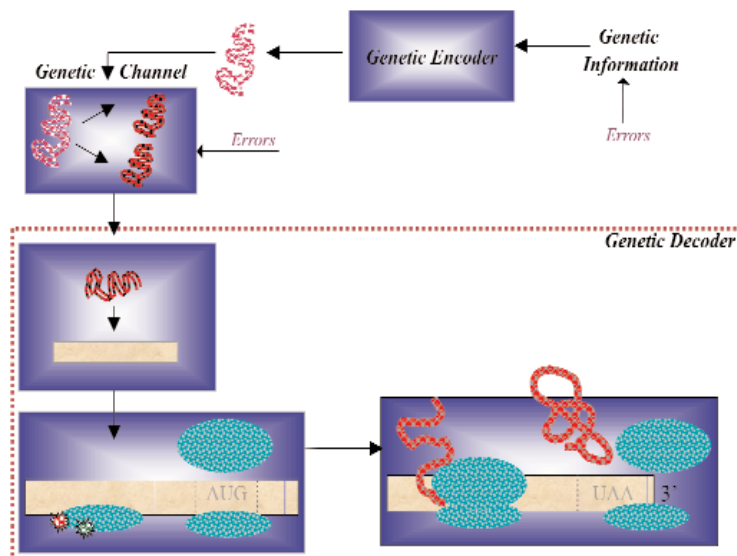


Figure 1. Communication View of the Central Dogma of Genetics

that what we as engineers endeavor to create is a mimicry of what nature has already perfected. As a case study, let us view the central dogma of genetics as an engineering communication system.

A fundamental challenge for engineering systems is the problem of transmitting information from the source to the receiver over a noisy channel. This same problem exists in a biological system. How can information required for the proper functioning of a cell, an organism, or a species be transmitted in an error-introducing environment?

hard to imagine that organic systems also recognize the need to protect their genetic message—the key to their survival and the survival of the species. We are extending Shannon information theory and coding theory concepts to study the complex system of information transmission in biological systems in hopes of forming a general understanding of biological communication mechanisms.

### So where does one begin?

We pick up from where the last quest ended fifty years ago, namely that the “cracked” or current genetic code is error tolerant and redundant. In other words



into the channel capacity of replication, possible correlation between an agent's mutation rate and the agent's pathogenicity, and the linearity of translation initiation sequences. Additionally our investigation concluded that advances in solver technology are needed in order to solve realistically sized code reconstruction problems.

The knowledge gained from biological coding research will contribute to our quantitative understanding of complex biological systems and provide insight for potentially modifying organisms of interest for applications in areas of national need, including biosensors, bioremediation and bio-terrorism defense. The ability to reconstruct the code model for translation regulatory sites in yeast or organisms used for biosensor applications will enable scientists to algorithmically design organism-specific regulatory sites that can increase the expression of engineered reporter genes. Ultimately we hope to acquire the knowledge for building "programs" or genomes for bio- and nanotechnology applications. Additionally, given the efficiency of bacterial and viral organisms, we suspect that prokaryotic life forms may have achieved the Shannon limit for information transmission rates. If that is the case, research investments into biological coding methods stand to yield unimaginable returns not only for

computational and experimental biology, but for communication engineering as well.

*Internal support for this work was provided by the Seniors Council Tier 1 LDRD. Team members: Elebeoba May (9212), Anna Johnston (9215), William Hart (9215), Jean-Paul Watson (9215), Rich Pryor (9216), and Mark Rintoul (9212).*

For a detailed description of this work see SAND2003-3963. ■

## Modeling and Simulation of Complex, Inter-dependent Adaptive Infra-structures

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National and economic security and indeed, the quality of life in the U.S., depend upon the continuous, reliable operation of a complex set of infrastructures that includes electric power, oil and natural gas, transportation, water, communications, banking and finance, emergency services, law enforcement, government continuity, agriculture, and health services. Each infrastructure is very complicated, formed from a large number of sub-components connected in

myriad ways. Each incorporates people who make decisions at scales from the individual, to cliques, to companies, to consortiums and larger groups. These infrastructures are made interdependent by complex and often poorly-understood linkages. These interdependencies allow disruptions in any single infrastructure to jeopardize the continuous operation of the entire system of infrastructures.

Understanding individual infrastructures and their complex interdependencies and vulnerabilities is essential for implementing effective policy for the enduring operation, regulation, and defense of the national infrastructure as a whole. This understanding requires the development of advanced modeling, simulation, and analysis capabilities. These capabilities are embodied within the National Infrastructure Simulation and Analysis Center (NISAC). A subset of these capabilities is created by the work of the Advanced Modeling Techniques Investigation (AMTI) Group.

Complexity Science has been used to explore commonalities among events as varied as: earthquakes, mass extinctions, major wars, traffic jams, major forest fires, epidemics, revolutions, landslides, stock market crashes, and major power outages. All of these events have something in common—although we are unable to fully explain their causes nor predict their

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**"Complexity Science has been used to explore commonalities among events as varied as: earthquakes, mass extinctions, major wars, traffic jams, major forest fires,... stockmarket crashes and major power outages."**

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“...complex systems are particularly resistant to investigation using the reductionist approach common to many scientific and engineering investigations in which detailed study of the system components is sufficient to understand the system as a whole.”

precise occurrences and magnitudes, they exhibit behaviors characteristic of systems that are “complex.” In general, complex systems are composed of many interacting parts with simple rules of behavior. One finds that these systems often yield behavior that is not intuitively obvious at the outset, that the whole is greater than the sum of the parts. Because of this, complex systems are particularly resistant to investigation using the reductionist approach common to many scientific and engineering investigations in which detailed study of the system components is sufficient to understand the system as a whole.

In recent years, a general theory for complex systems has emerged that suggests there is a natural tendency for diverse complex systems to “self-organize” into what is called the “critical state,” a state of instability often described as being at the “edge of order and chaos.” In such a state, cascading events of all sizes can occur at any time and thus are unpredictable except through measures of their statistics. The behavior (e.g., the propensity to cascade) and resiliency (e.g., attack vs. error tolerance) of the complex system has also been found to depend on the statistical characteristics of complex networks. Additionally, there is a growing realization that many such systems adapt, especially when people or biological processes are integral to the system, and

thus are aptly described as “Complex Adaptive Systems” or CAS. Here, the two aspects of complex systems, their behavior and underlying network structure, are intertwined with feedbacks that cause the system to evolve. Research on CAS has found that networks evolving within one “network ecology” can be particularly susceptible to disruption when the nature of the threats changes.

Let us consider an infrastructure as a network of nodes, connected to each other by links through which some form of material or information flows. Nodes could be: power plants, transformers, power grid loads, computers and routers on the internet, institutions in a financial network, transportation hubs (airports), telecommunications hubs, or people (individuals or groups) in a social network. The geometric configurations, or topologies, of these networks can be further abstracted to allow systematic study of the more general or generic infrastructure. We can define simple abstracted rules for node behavior as well as rules for the interaction of one node with another on the abstracted network. The abstract infrastructure is now entirely analogous to those studied in Complexity Science. We may now ask ourselves questions about how abstract interdependent infrastructures respond to disruptions, such as:

- How can seemingly small initiating events (e.g., single

point equipment failures) cascade into large infrastructure network disruptions?

- Is it always straightforward to identify the critical nodes in a system and protect them from failure?
- How does the structure of the connectivity between nodes affect network stability?
- Can we develop improved indicators of an infrastructure’s status?
- How can we use simulations of networks abstracted from real infrastructures to look for unintended consequences of proposed policy?
- Are there general lessons to be learned about infrastructure networks that can be applied across many systems obviating study of each infrastructure in excruciating detail?

The provocative findings of Complexity Science concerning cascading failures on the one hand, and topological resiliency on the other, raise questions regarding possible inherent susceptibilities to collapse, or easily exploited weaknesses in infrastructures that arise from simple rules for node dynamics or from the infrastructure topology. Depending on the answers, a strategy of identifying and selectively protecting “critical nodes” may ultimately prove to be unavailing and a more nuanced approach for evolving robust



infrastructures might be indicated. Additionally, infrastructures change over time; system behavior and system structure are inherently linked and evolve through adaptive feedback. Complexity Science suggests that “scale-free” networks that have evolved in a “network ecology” optimized for a tolerance to random node outages (characteristic of water, electricity, natural gas and other distribution systems) are particularly susceptible to directed attacks. As another example, consider the current “business ecology” where market liberalization encourages leanness and imposes pressures on key infrastructures to cut overheads (often by building out redundancy). Based on principles uncovered in the context of Complexity Science, policies that encourage infrastructure efficiency during normal operations may make these infrastructures less robust in response to disruptions.

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## The Earth System and Global Climate Change

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A recent article in the *Albuquerque Journal* said that January and July of 2003 set records as the warmest in Albuquerque history. But the city’s history isn’t that long, and thermometer records haven’t been kept for much more than a century. Scientists who want to study the long-term record of weather must use the tools of paleoclimatology.

Paleoclimate researchers are able to extract older data from historical records of blossom dates in the spring, harvest dates in the fall, and documentation of when harbors were ice-free. Older recorders of climate information include tree rings, stalactites, stalagmites, fossil pollen, and coral reefs. The Greenland ice sheet has yielded two miles of core that goes back more than 100,000 years. Ocean sediments that are millions of years old have been drilled and examined.

Oxygen isotope data is one “proxy” record of temperature and land ice volume. A graph of the data over time looks like a stock ticker chart, with episodes of sharp ups and downs, sometimes followed by periods of remarkable

stability. Close examination shows there are cycles in the data with various periods ranging from decades to 100,000 years. Like cyclic stocks, the periodicities are not perfect and predictable. Ice-ages come and go with a period of about 100,000 years. But it used to be 40,000 years, and there is still a “40 kyr” signal in the power spectrum of marine sediments.

Like the stock market, climate does not seem to have a single preferred state. It jumps around because of multiple nonlinear responses to both internal and external forces at different levels of organization. Sometimes it seems fixed and solid—as it has been for the past 10,000 years—with an occasional uptick (like the Medieval warm period, when the Vikings settled Greenland), or downtick (like the “Little Ice-age,” during which the Greenland colonies collapsed and George Washington spent a winter at Valley Forge). Other times it can go through a major “correction,” such as the end of the last ice age, when the warming trend suddenly reversed itself and Europe was blessed with another 1000 years of winter before jumping nearly 10 degrees in about a decade.

Like stock market analysts, climate scientists are in the position of having the past to analyze and explain. And there are expectations (despite disclaimers) that they should be able to predict future performance. This is a

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**“Like the stock market, climate does not seem to have a single preferred state.”**

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daunting task, but climatologists don't have the luxury of being able to test their models against the daily market. Climate unfolds much more slowly.

Earth system science is an emerging discipline that is focused on global change and its affects on life. Understanding the Earth system requires that its component systems and their interactions be understood on time scales ranging from seconds to millions of years. Components include the atmosphere, hydrosphere, geosphere, cryosphere (land and sea ice), and biosphere.



Interactions include the physical, chemical, and biological processes that cycle heat, moisture, and chemicals within and among the components.

Viewed through the lens of Earth system science, our planet is a coupled, nonlinear dynamic system of physical, chemical, and biological systems.

As a system dominated by life, the Earth itself can be considered to be a complex adaptive system. The extent to which the Blue Planet is self-organizing is controversial, but complexity theory has been applied to help understand the emergence of order. In 1983, A. J. Watson and J. E. Lovelock published a paper called *Biological homeostasis of the global environment: the parable of Daisyworld*.

In Daisyworld, there are white daisies that reflect sunlight, and black daisies that absorb it. The plants grow at a rate that depends only on local temperature; they are cellular automata. In doing so, they automatically adjust the albedo of Daisyworld in a way that keeps its temperature surprisingly constant over a wide range of external forcing (such as solar variability).

Daisyworld is just a conceptual model that was conceived to illustrate an idea, but the real Earth does exhibit some Daisyworld-like tendencies, which have come to be described by various forms of the Gaia theory

In the real Earth, organisms control atmospheric chemistry. When plants discovered photosynthesis, the atmosphere became oxygen-rich. This radically changed the way minerals weathered, changing the chemistry of the surface rocks and the ocean. It also changed the direction of evolution, and oxygen-breathing animals were allowed to exist.

Sequestration of carbon dioxide by plants reduces the long-wave radiation opacity of the atmosphere, regulating greenhouse warming in a way that sustains those organisms—much like Daisyworld. If an organism were to evolve that modified the atmosphere in a way that were not sustainable for its own life, it would either adapt and evolve into the new niche it created for itself, or it

would go extinct and be replaced by something else.

We are living in such a world, where one organism is now modifying the atmosphere in a way that may require co evolutionary change to ensure its survival. That organism is part of another complex adaptive system: human society. Society has already evolved in response to one atmospheric response to its chemical modification—it has banned chloro-fluorocarbons.

It remains to be seen how the human system will interact with the climate system in other ways, over other time scales, and at other levels of organization. Modeling these two systems together will be a challenging, but necessary task. ■

## Modeling Human Adaptation to Climate Change as a Complex Systems Response

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The security of the U.S. will soon be challenged by a new threat. Dramatic changes in global climate caused by a combination of natural and human induced influences are expected this century. As global climate changes,



human societies will respond with adaptive behaviors that might include migration, increased energy consumption, and forced conservation. These stresses could lead to changing global alliances and could lead to civil unrest and war as populations shift and vie for territory and natural resources. Preparing for these changes will require advanced understanding of the potential impacts of these events. The complexity of this problem arises from the interactions between human societies adjusting to changing climate and from both positive and negative feedback with the environment. Analysis and modeling of the response requires a complex systems view that not only accounts for the physics of climate change but a methodology to predict the likely impacts of climate stresses on international alliances and trade networks.

Previously, economists and social scientists have attempted to determine the impacts and costs of climate change by various modeling and simulation strategies. Most have treated climate change as a boundary condition, and those that seek to incorporate climate processes (i.e. MIT Global System Model) treat much of the environmental and economic feedbacks at a

global level. Using a global approach leads to assumptions that can be completely misleading and deceptive for simulating society response because these "on average" conditions will not reflect true local



stresses. We suggest that human adaptation to climate change will occur at a local level and that these local impacts will lead to global societal issues. We therefore believe that any credible simulation of the economic, political and social costs of climate change must take a complex systems approach and incorporate feedback dynamics at a local or regional level.

Representing climate change variability and human adaptation as a complex adaptive system will provide a greater understanding of how patterns and processes might emerge and interact across the globe and across spatial and temporal scales. We expect, because climate

change will not be uniform, that there will be differences among regions in its affect on temperature, precipitation, and other key environmental variables. These in turn, will have an effect on agricultural production, transportation, heating, cooling costs, and so on. The economic response in turn will affect greenhouse gas production of a particular location through changes in land use, fuel consumption, and economic activity. This economic feedback on the climate system is the second component of the bi-directional feedback system.

Sandia is in a unique position to apply expertise in massively parallel simulation and modeling to achieve the local/regional analyses that is required to address this problem. Uncertainty about climate change is not a limitation to planning. Simulation tools designed to represent complex systems will allow decision makers to analyze a wide range of climate change scenarios and subsequent societal disruptions. Ultimately the application of complex systems science to understand human response to climate change might allow decision makers to prepare necessary adaptation strategies and invest in the infrastructure support and technological innovations necessary to adapt to imminent climate change. ■

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## Happy Thanksgiving!